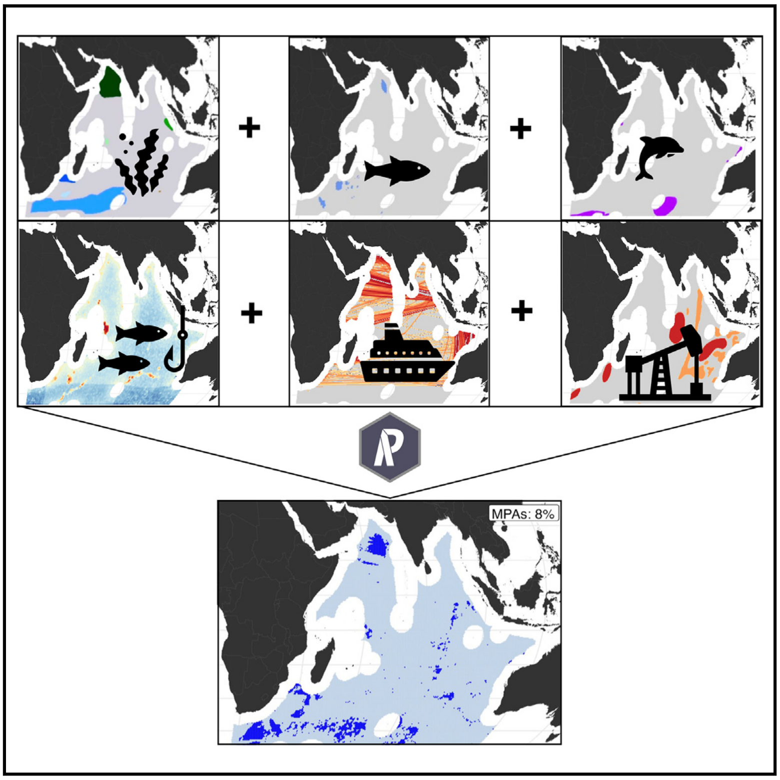
One Earth

Article

Generating affordable protection of high seas biodiversity through cross-sectoral spatial planning

Graphical abstract



Authors

Léa Fourchault,
Farid Dahdouh-Guebas,
Daniel C. Dunn, ..., Kanthi K.A.S. Yapa,
Stefano Cannicci,
Anthony J. Richardson

Correspondence

lfourchault@naturalsciences.be (L.F.),
anthony.richardson@csiro.au (A.J.R.)

In brief

Marine life in the open ocean is increasingly disturbed by human activities. Using a cross-sectoral approach to design protected areas can mitigate the negative impacts of fishing, shipping, and deep-sea mining. This approach also ensures a minimal loss of economic activity for each sector.

Highlights

- Sector-specific marine protected areas induce high economic losses across sectors
- A cross-sectoral approach reduces economic losses for all sectors
- A cross-sectoral approach reduces the area needed to meet conservation objectives
- A cross-sectoral approach protects biodiversity against impacts from all sectors

Fourchault et al., 2024, One Earth 7, 1–12
February 16, 2024 © 2023 Published by Elsevier Inc.
https://doi.org/10.1016/j.oneear.2023.12.006

Please cite this article in press as: Fourchault et al., Generating affordable protection of high seas biodiversity through cross-sectoral spatial planning, One Earth (2023), https://doi.org/10.1016/j.oneear.2023.12.006

One Earth

CellPress

Article

Generating affordable protection of high seas biodiversity through cross-sectoral spatial planning

Léa Fourchault,[1,2,11,*] Farid Dahdouh-Guebas,[1,2,3] Daniel C. Dunn,[4,5] Jason D. Everett,[6,7] Jeffrey O. Hanson,[8] Kristine C.V. Buenafe,[4,7] Sandra Neubert,[4,7] Alvise Dabalà,[1,2,4,7] Kanthi K.A.S. Yapa,[9] Stefano Cannicci,[10] and Anthony J. Richardson[5,6,7,12,*]

[1]Systems Ecology and Resource Management, Department of Organism Biology, Université Libre de Bruxelles (ULB), Brussels, 1050 Brussels Region, Belgium

[2]Systems Ecology and Resource Management, Department of Biology, Vrije Universiteit Brussel (VUB), Brussels, 1050 Brussels Region, Belgium

[3]Interfaculty Institute of Social-Ecological Transitions, Université Libre de Bruxelles (ULB), Brussels, 1050 Brussels Region, Belgium

[4]School of Earth and Environmental Sciences, The University of Queensland, Brisbane, QLD 4072, Australia

[5]Centre for Biodiversity and Conservation Science (CBCS), The University of Queensland, St Lucia, QLD 4072, Australia

[6]Commonwealth Scientific and Industrial Research Organisation (CSIRO) Environment, St Lucia, QLD 4072, Australia

[7]School of Environment, The University of Queensland, St Lucia, QLD 4072, Australia

[8]Department of Biology, Carleton University, Ottawa, ON K1S 5B6, Canada

[9]Department of Physics, University of Ruhuna, Matara, Southern Province 81000, Sri Lanka

[10]Department of Biology, Università degli Studi di Firenze, Sesto Fiorentino, 50019 Firenze, Italy

[11]Present address: Royal Belgian Institute of Natural Sciences, Brussels, 1000 Brussels Region, Belgium

[12]Lead contact

*Correspondence: lfourchault@naturalsciences.be (L.F.), anthony.richardson@csiro.au (A.J.R.)

https://doi.org/10.1016/j.oneear.2023.12.006

SCIENCE FOR SOCIETY With increasing open-ocean industrial activities and governance structures still in development, negative impacts on marine biodiversity are growing. Collaboration among ecologists, data scientists, sociologists, and economists is needed to identify optimal locations to establish protected areas. These locations should meet conservation targets while minimizing economic losses to the industrial sectors they constrain. Concurrent consideration of multiple industries generates efficiency in the extent of the area required to ensure ecosystem services and better protects marine life against cumulative industrial impacts. This will help safeguard marine life and the ecosystem services it provides, including food, oxygen, climate stability, and medical innovations.

SUMMARY

Over the past 20 years, industrial activities have accelerated in the open ocean. Fishing, shipping, and deep-sea mining are major drivers of this "blue acceleration," with each having its own suite of impacts on species, communities, and ecosystems. We use a systematic conservation planning approach combining ecological and socioeconomic data from the fishing, shipping, and deep-sea mining sectors to examine the utility of a cross-sectoral approach. Applying our framework to the Indian Ocean, we show that the cross-sectoral spatial plan meets the same conservation targets at a lower overall cost and using a smaller area compared with sector-specific plans implemented simultaneously. In addition, we identify areas that are best suited to conservation using a replacement cost metric. Our approach ensures affordable biodiversity protection throughout the water column and can serve as a first step toward the implementation of the recently signed High Seas Treaty.

INTRODUCTION

Since the 1950s, industrial activities have expanded into the open ocean, driven by diminishing resources and technological developments.[1,2] In recent decades, this "blue acceleration" has seen a greater diversity of stakeholders interested in resources in areas beyond national jurisdiction (ABNJs; i.e., the high seas and international seabed beyond exclusive economic zones[3]). Recognizing the need to meet increased use of ABNJs with a holistic governance structure, the United Nations have recently agreed upon an international legally binding instrument for the conservation and sustainable use of marine biological diversity in ABNJs.[4] A key element of this new treaty is the articulation of a mechanism for the implementation of area-based management tools in ABNJs, including marine protected areas (MPAs). While the treaty does not specifically protect any part of ABNJs and there will be challenges in implementation, the development of a mechanism to designate MPAs in ABNJs is critical to the delivery of Target 3 of the Montreal-Kunming Global Biodiversity Framework (CBD 2022, CBD/COP/15/L.25), which sets out the latest area-based targets for conservation of terrestrial and marine environments (i.e., 30% by 2030).[5]

To inform the design of MPAs, systematic conservation planning leverages ecological and socioeconomic data and optimization algorithms.[6–9] In the 20th century, the fishing sector was arguably the most important maritime stakeholder and the greatest impact on oceanic biodiversity.[10,11] Thus, MPAs have been generally designed to minimize conflict with the fishing sector,[12,13] ignoring other major stakeholders such as shipping and mining. Consequently, marine organisms can be poorly protected against impacts linked to maritime transport[14] and seabed exploration for mineral extraction[15,16] (e.g., collisions, pollution, habitat degradation). The single-sector focus of conservation planning in coastal and oceanic areas has led to the compartmentalization of conservation strategies due to competing priorities among sectors, with deleterious impacts on biodiversity.[17,18]

The inclusion of multiple stakeholders in systematic marine conservation planning has been recognized as a major technical challenge.[19] Except for fishing revenue, the monetary value of human uses of marine space and resources is rarely available, hence complicating the generation of a single-unit cost layer with a common unit across human uses of the ocean.[20,21] This approach to marine spatial planning is inequitable, placing all the conservation burden on the fishing sector. It also fails to acknowledge the potential impacts other sectors may have on marine biodiversity. As sectoral divisions may further hinder implementation, it is important to develop multisectoral approaches for the placement of MPAs.[22]

While MPAs in ABNJs have been implemented in the North Atlantic[23] and the Southern Ocean,[24] there are none in international waters in the Indian Ocean, despite the rapid expansion of human activities there. Fishing effort is predicted to increase due to ongoing fleet motorization and population growth within coastal nations.[25,26] In addition, merchant shipping will grow as China develops cooperation strategies with African nations.[27] The Indian Ocean is also a mineral-rich region, with potentially imminent exploitation of polymetallic sulfides and nodules along the Southwest Indian Ridge and Central Indian Ocean Basin and ongoing research of cobalt-rich crusts.[28] These threats pose risks for endangered local megafauna, such as the Indian pygmy blue whale *Balaenoptera musculus indica* Blyth (1859) and the whale shark *Rhincodon typus* Smith (1828).[29,30] Seamounts and plateaus in this region also host vulnerable deep-sea fish and ecosystems, whose slow growth rates have made them vulnerable to commercial exploitation.[31,32] In addition, 60% of vent mollusks in the Indian Ocean are critically endangered, and 100% of them are threatened, which is the highest value among global biogeographic regions.[33] Given the increasing use of this biodiverse region and the new mechanism for developing MPAs in ABNJs, developing MPAs that are equitable across sectors in the open ocean and deep sea of the Indian Ocean is crucial.[34]

Here, we assess the potential trade-offs associated with including multiple stakeholders in a cross-sectoral marine spatial plan for ABNJs in the Indian Ocean. We first created three sector-specific spatial plans to identify optimal locations for no-take MPAs, ensuring that conservation targets are met at a minimal cost to the fishing, shipping, and deep-sea mining sectors. We then created a cross-sectoral no-take spatial plan that minimizes the opportunity cost to all stakeholders simultaneously. After generating the spatial plans, we compared the three sector-specific solutions, as well as their union, to the cross-sectoral solution. Our analysis shows that explicitly accounting for different sectors in cross-sectoral conservation planning can achieve Target 3 of the Kunming-Montreal Global Biodiversity Framework (CBD 2022, CBD/COP/15/L.25) at an affordable cost for all stakeholders and at a lower cost than if all sector-specific plans are implemented without coordination. This ensures at least 30% coverage for important biodiversity features, including key life-cycle areas for marine megafauna, areas of biological and ecological interest, and areas important to deep-sea ecosystems (e.g., seamounts, vents, and plateaus). The early engagement of stakeholders into cross-sectoral spatial planning processes will thus facilitate cost-effective implementation of the recently signed High Seas Treaty.[8,13]

RESULTS

Sector-specific conservation

Sector-specific plans differed in terms of size, spatial distribution of MPAs, and areas of higher importance. The fishing-specific plan protected 2.6 million km^2 (7.8% of the planning region across both the western and the eastern Indian Ocean; Figure 1A). This resulted in a relative opportunity cost of 19.5% to the fishing sector (Table 1), where the relative opportunity cost is the percentage of the total possible foregone economic activity for that sector. MPAs with planning units having the highest replacement cost (i.e., where the protection of biodiversity cannot be achieved elsewhere at a lower cost) for the fishing sector were on the Mascarene Plateau (northeast of Madagascar; see Figure S1 for all locations mentioned in the text) and in the southwestern Indian Ocean, along the Agulhas Front and the southern Mozambique Channel (Figure 1B). In these areas, high-value fishing areas (>10,000 USD year^{-1}) overlap with two or more conservation features, driving up the cost of each planning unit. By contrast, the shipping-specific plan protected 5.6 million km^2 (16.9% of the planning region, resulting in a relative opportunity cost of 0.6% for the shipping sector), with no MPAs protecting the easternmost conservation features, such as Important Marine Mammal Areas, which were cheaper to protect in the southern Indian Ocean (Figure 1C). Planning units with the highest replacement cost for the shipping sector were in the Arabian Sea (Figure 1D), where dense shipping routes (>100,000 ships year^{-1}) overlap with two or more conservation features. Finally, the mining-specific plan protected 7.3 million km^2 (21.8% of the planning region, resulting in a relative opportunity cost of 1.6% for the mining sector; Figure 1E).

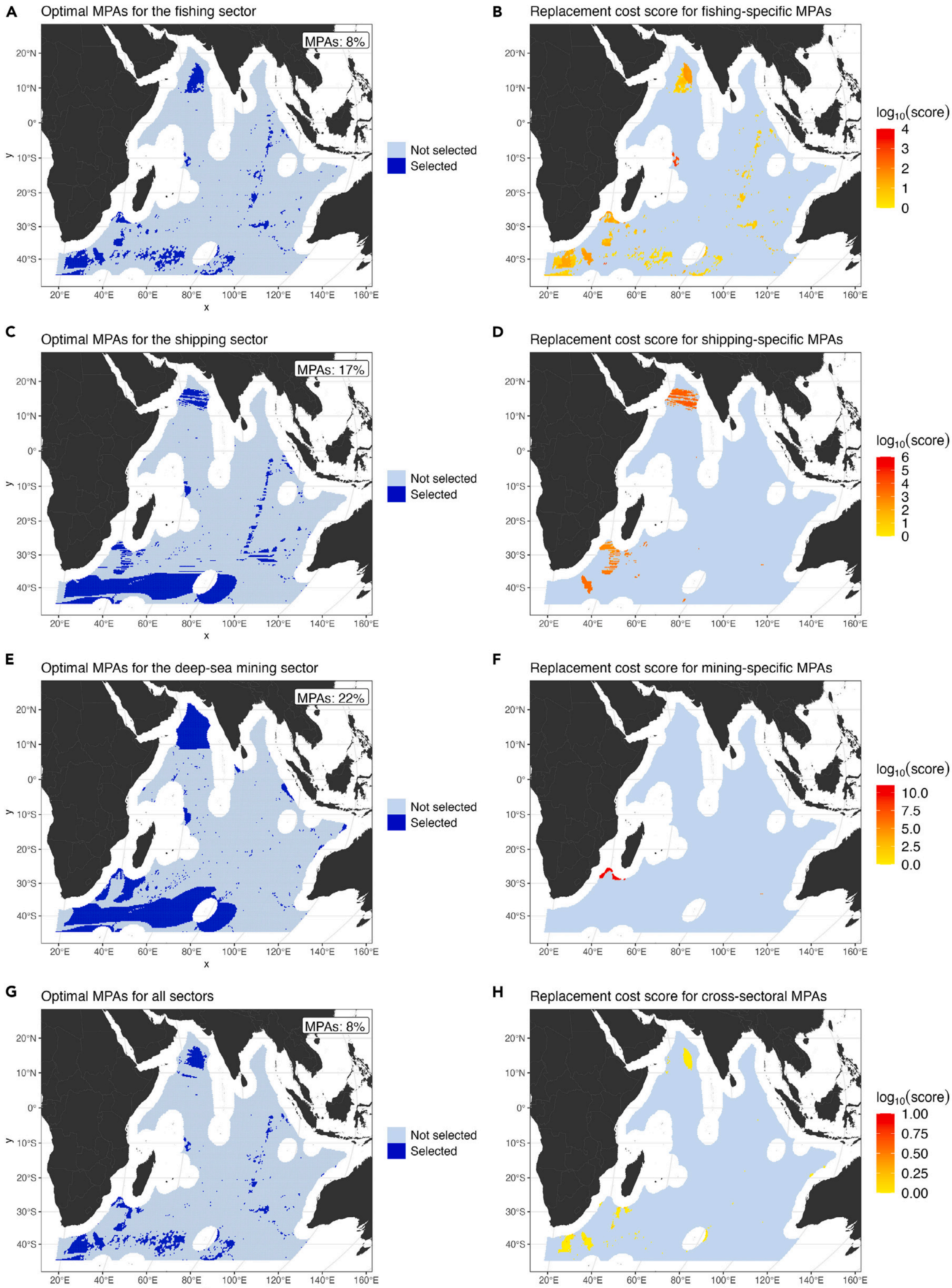


Figure 1. Optimal spatial plans and their corresponding replacement cost score

Optimal planning units are selected (dark blue) to become part of the spatial plan (A, C, E, and G). The replacement cost score of each selected planning unit is also shown (B, D, F, and H). Higher values of the replacement cost score indicate that planning units are more expensive to replace and are thus more important for achieving the conservation targets while minimizing the opportunity cost.

Table 1. Protected areas characteristics

	Surface area (×1,000 km^2) (% of the planning region)	Cost to the fishing sector (relative cost)	Cost to the shipping sector (relative cost)	Cost to the deep-sea mining sector (relative cost)
Fishing-specific plan	2,606 (7.8%)	3.7 (19.5%)	159.0 (7.5%)	19,000,000 (5.4%)
Shipping-specific plan	5,639 (16.9%)	7.0 (36.6%)	13.2 (0.6%)	23,000,000 (6.6%)
Deep-sea-mining-specific plan	7,274 (21.8%)	9.8 (51.1%)	539.0 (25.5%)	5,420,000 (1.6%)
Union of all three sector-specific plans	8,084 (24.2%)	10.2 (53.5%)	556.0 (26.3%)	27,000,000 (7.7%)
Cross-sectoral plan	2,522 (7.6%)	3.8 (20%)	21.2 (1%)	6,980, 000 (2%)

Relative cost is the opportunity cost incurred as a result of foregone economic activity in a given spatial plan, expressed as a ratio of the total possible sector-specific opportunity cost if MPAs encompassed the entire planning region. This allows for the comparison of costs expressed in different units: fishing, USD 100,000 year^{-1}; shipping, 100,000 ships year^{-1}; deep-sea mining, USD 100,000.

Planning units with the highest replacement cost for the deep-sea mining sector were selected in the southern Mozambique Channel (Figure 1F), where polymetallic nodule fields (>1,000,000,000 USD) overlap with conservation features.

The degree of agreement as measured by Cohen's κ coefficient[35] varied considerably between the sector-specific plans. The agreement between mining-specific and shipping-specific plans was substantial (κ = 0.72), driven by the similarity in selected areas in the southern Indian Ocean, such as the Agulhas Front region, where both sectors have minimal activities. However, mineral-rich eastern plateaus are not protected in the mining-specific plan, whereas both the fishing- and the shipping-specific plans select this area for protection. Overall, both the mining- and the shipping-specific plans had a lower agreement with the fishing-specific plan (κ = 0.36 and κ = 0.43, respectively).

Cross-sectoral conservation

In the cross-sectoral plan, MPAs spanned 2.5 million km^2 to meet the conservation targets (7.6% of the planning region; Figure 1G and Table 1). This is similar to the fishing-specific plan and lower than the mining- and shipping-specific plans. This plan protected areas in the southern Indian Ocean, the eastern plateaus, and parts of the Arabian Sea, except for major shipping routes along 10°N. Planning units with the highest replacement cost for the cross-sectoral plan were selected in the western Agulhas Front and the central Arabian Sea, where conservation features overlap with shipping routes and/or high-value fishing areas. It most closely resembled the fishing-specific plan (κ = 0.85), except for MPAs in the Arabian Sea, which were more similar to MPAs of the shipping-specific plan in that region. By contrast, the agreement of the mining- and shipping-specific plans with the cross-sectoral plan was weak (κ = 0.39 and κ = 0.46, respectively).

The cross-sectoral plan yielded slightly more expensive, but still comparatively affordable MPAs for all sectors (Table 1). Specifically, opportunity costs incurred by the fishing sector increased from 19.5% (fishing-specific plan) to 20% (cross-sectoral plan). For shipping and mining sectors, opportunity costs increased from 0.6% to 1% and 1.6% to 2% from the sector-specific to the cross-sectoral plan, respectively. As such, the additional relative opportunity cost for each sector when considering other sectors is 0.5% for the fishing industry and 0.4% for the shipping and deep-sea mining industry. By contrast, the relative costs in the cross-sectoral plan are lower for all sectors than the costs incurred by every sector if all sector-specific plans are implemented simultaneously. For instance, the fishing sector may lose 20% of its potential revenue in the cross-sectoral plan, but it would lose 54% if all sector-specific plans were implemented simultaneously without coordination (i.e., an additional relative opportunity cost of 34%). This finding was also consistent for the shipping and mining sectors, with the shipping sector losing 26% of its potential revenue and the mining sector losing close to 8% (i.e., an additional relative opportunity cost of 25% and 6%, respectively) if all sector-specific plans were implemented instead of the cross-sectoral plan.

DISCUSSION

We showed that the fishing-specific spatial plan differed substantially from the mining- and shipping-specific plans, which highlights the importance of considering different sectors when designing MPAs. In addition, the cross-sectoral plan can meet the same conservation targets at much lower additional costs for each stakeholder than if all sector-specific plans are implemented without coordination. These findings emphasize both the importance and the feasibility of cross-sectoral conservation planning in ABNJs, which is key to better protecting marine ecosystems against the negative impacts of fishing, shipping, and deep-sea mining.

The disparate distribution of sectoral activities drives differences in plans

The dissimilarity of the fishing-specific plan to the other sector-specific plans is a consequence of two aspects of the fishing opportunity cost data. Opportunity cost for each sector is driven by the geographic distribution of activities or potential future activities. These areas are largely not spatially congruent across sectors. For instance, while fishing overlaps with biodiversity features south of 37°S, both mining and shipping cost datasets have near-zero costs for planning units located south of 37°S. This results in the selection of >1,000 planning units (>1,000,000 km^2) in this region for the shipping and mining sectors (see Figures 1 and 3). Second, high-value areas for each sector were geographically dispersed. Most high-value planning units for the fishing sector are in the southern and western Indian Ocean, especially surrounding the Mascarene Plateau, where tuna, emperor, and grouper

Please cite this article in press as: Fourchault et al., Generating affordable protection of high seas biodiversity through cross-sectoral spatial planning, One Earth (2023), https://doi.org/10.1016/j.oneear.2023.12.006

are key commercial species.[36] By contrast, the most high-value planning units for the deep-sea mining sector are in the central (polymetallic nodules) and eastern (cobalt-rich crusts) Indian Ocean.[28,37] Similarly, the most high-value planning units for the shipping sector are routes linking Asia with Australia in the east and with the Mediterranean Sea in the center north,[38] away from major ABNJ fishing grounds. Thus, differences in the sector-specific plans are driven by the broad distribution of fisheries, compared with the concentrated mineral resources or shipping routes.

The importance of the differences in the distribution of opportunity costs among sectors also affects the size of the area being protected in each plan. Notably, the cross-sectoral plan required less area to meet the set conservation targets than any sector-specific plan (Table 1). When opportunity costs are combined across sectors, the number of planning units with no opportunity cost decreases, leading the prioritization algorithm to be more selective, thus reducing the size of the MPAs generated. Because fisheries operate more broadly than shipping or deep-sea mining, the fisheries-specific plan was the second smallest. By contrast, the shipping and deep-sea mining plans contain numerous planning units of no cost that overlap with biodiversity features, thus generating much larger solutions. While opportunity cost is central to considerations of equity among industries in developing these plans, generating a smaller overall MPA network size is critical for feasibility and enforcement.

Sector-specific MPAs: Differing priorities

The fishing-specific plan also has high relative opportunity cost. This is reflected in the replacement cost scores for the Saya de Malha Bank seagrass bed on the Mascarene Plateau, which was given a protection target considering its importance to reef fish, tuna, and marine mammals such as the endangered pygmy blue whale *B. musculus indica*.[39] Removing this conservation feature decreases the relative opportunity cost for the fishing sector from 19.5% to 2.6% (a summary of the economic impact of each conservation feature on each sector is available in Table S1). However, protecting the Saya de Malha Bank is important for eastern African countries such as Somalia, where coastal waters are strongly linked to the high seas through the South Equatorial Current, which flows over the Mascarene Plateau.[40] This current enhances larval circulation toward the coast, thus supporting traditional fisheries in low-income countries.[40,41] By contrast, allowing extensive fishing in the Mascarene Plateau and other ABNJs would negatively affect traditional coastal fisheries through downstream genetic impoverishment and reduced recruitment, while minimally contributing to global food security.[42] Further, as 97% of the fishing vessels in ABNJs are flagged to high-income countries and benefit from government subsidies to remain profitable, the benefit to local economies is often minimal.[43,44] Therefore, establishing MPAs in these high-value fishing grounds in the Indian Ocean will ensure wide socioecological benefits despite a high opportunity cost for high-seas fishing fleets.

Unlike high-value fishing grounds, maritime transport routes are not correlated with higher biodiversity, and MPAs can be designed around them. This yields low-cost spatial plans with large shipping-specific MPAs, with a relative opportunity cost two orders of magnitude lower than that of fishing-specific plans. Because low-cost cells could be chosen, the area selected is vast, resulting in a solution that exceeds three times as many conservation targets (Figure S2). Critically, while shipping-specific MPAs did not include the easternmost Important Marine Mammal Areas, which could be selected at a lower cost in the southern Indian Ocean, they protect features in the Arabian Sea despite high traffic, as highlighted by high replacement cost scores. This is crucial, as this region has high shipping-related threats,[45] such as chronic low-level pollution from ship-based formaldehyde discharge[46] and total-loss cargo accidents.[47] Further risks linked to maritime transport include unreported ship strikes, which are likely to be responsible for the limited recovery of some marine megafauna species, such as the whale shark, whose populations continue to decline despite protection.[14] Given that numerous deep-sea organisms rely on pelagic subsidies, such as whale falls, the preservation of megafauna is key to maintaining deep-sea ecosystems.[48] Consequently, excluding busy shipping routes from MPAs is both beneficial and affordable in ABNJs.

While mineral-rich areas may overlap with ecological features, such as hydrothermal vents, seamounts, or plateaus,[37] the mining-specific plan also yields large MPAs of low relative opportunity cost. Specifically, the plan uses three times more space than the fishing-specific plan and exceeds three and a half times the number of conservation targets (Figure S2), for a relative opportunity cost an order of magnitude lower than for the fishing sector. The weak overlap between mineral-rich areas and conservation features is also highlighted by the few planning units exhibiting a high replacement cost score, all of which are in the ABNJ of the Mozambique Channel, where mining is unlikely to take place before polymetallic nodules in the central Indian Ocean become depleted.[28] Critically, no MPA was generated to protect the cobalt-rich eastern plateaus, as plateaus could be protected at a lower cost in the western Indian Ocean. Considering growing demand for cobalt, these plateaus are nonetheless likely to be mined.[28] Negative impacts of deep-sea mining on biodiversity, such as gill clogging or habitat destruction, are likely to take decades to return to normal, as deep-sea species show slow rates of recovery after disturbance.[49] Further, once deep-sea mining begins at industrial levels, its footprint will be larger than the directly affected seafloor itself because of sediment and discharge plumes that spread over several kilometers.[50] Providing buffers around MPAs in mineral-rich ABNJs would reduce their proximity to metal-laden plumes and will ensure persistent protection regardless of growing global demand for copper, nickel, and cobalt.

Cross-sectoral MPAs: An affordable compromise

The cross-sectoral plan better protects organisms against both sector-specific and cumulative impacts from industrial uses of ABNJs.[45] Further, its optimal integration of multiple socioeconomic interests will facilitate implementation.[18,22]

The intrinsic conservation advantage of cross-sectoral plans over sector-specific plans is the protection from all sector-specific threats—direct exploitation, bycatch, close-range interactions, habitat degradation—and their cumulative effects.[16,45]

Cumulative impacts are especially important for organisms at higher trophic levels, such as pelagic predators. Seabirds, for instance, are frequently caught as bycatch, but may also see their habitats degraded by shipping and potentially by deep-sea mining activities, in addition to some of their prey being directly extracted by the fishing sector.[45] Further, their prey may suffer from warm or toxic discharge waters and other deep-sea-mining-related activities.[15,16,50] The generated cross-sectoral plan implies a ban on all fishing, shipping, and mining activities within the water column and seafloor of selected planning units, thus ensuring the mitigation of cumulative impacts from surface to seabed. Where deep-sea communities depend on pelagic subsidies, such as prey or detritus, protecting vertical ecological connectivity is crucial.[48] Cross-sectoral no-take MPAs may thus better protect both individual species and communities by maintaining habitat quality and trophic relationships.

Employing a cross-sectoral approach to conservation also has numerous political advantages. First, the cross-sectoral spatial plan is feasible with low additional opportunity costs for each stakeholder. With an additional relative opportunity cost of 0.4% for the shipping and mining industries, and of 0.5% for the fishing sector, the proposed cross-sectoral spatial plan met all conservation targets. The economic advantage is especially notable when the cross-sectoral plan is compared with the simultaneous implementation of each sector-specific plan, which results in a 2- to 20-fold increase in opportunity costs. Second, the cross-sectoral plan selected fewer planning units than sector-specific plans, resulting in a slightly smaller total area protected. This is driven by having fewer no-cost cells, which allows the selection of fewer but more expensive planning units. The selection of fewer planning units may help reduce enforcement costs.[51] Third, the cross-sectoral plan is most similar to the fishing-specific plan. This similarity will facilitate implementation, considering the importance of the fishing sector in negotiating MPA boundaries in ABNJs.[52] Last, cross-sectoral, strategic environmental assessments on a basin scale provide opportunities to identify the most efficient places to meet conservation targets across a broader range of options, resulting in cheaper, more efficient plans than can be developed by multiple, smaller-scale sectoral plans (e.g., the International Seabed Authority [ISA] focusing on the Mid-Atlantic Ridge, rather than a basin-wide approach). The approach developed may therefore support not only efforts to reach the 30 × 30 target, but also the United Nations' push for better cooperation between sectoral management organizations.[7,22,53,54]

While we advocate for the use of no-take cross-sectoral MPAs, other effective conservation measures (OECMs) can have the dual advantage of mitigating seasonal pressures when well managed and offering greater flexibility to specific stakeholders.[17,55] In the marine realm, OECMs have proven useful to maintain biodiversity through appropriate fisheries management.[56,57] As such, cross-sectoral core MPAs could be complemented with conservation-sensitive fisheries closures in areas where the fishing industry would incur the highest losses, as shown by the replacement cost score metric.[58] OECMs could also complement the cross-sectoral approach developed by creating seasonal buffers around deep-sea mining activities to better mitigate the risk of pollutants being transported downstream by seasonal currents.[16,50] Further, dynamic spatial management might be especially appropriate to mitigate impacts of climate change, particularly regarding fisheries. Indeed, warming has impacts on productivity,[59] fish distributions,[60] and migrations,[61–63] which increase the likelihood of conflicts in fisheries management.[64] Finally, creating seasonal "stepping stones" in-between reserves to account for migratory behaviors could ensure effective connectivity among MPAs.[40,65]

While ecological connectivity is not explicitly considered in our spatial plans, both sector-specific and cross-sectoral plans offer opportunities for connectivity with MPAs in national waters of neighboring countries. In the southwest, MPAs in ABNJs could be connected to MPAs in Madagascar, Mozambique, and South Africa via the Agulhas Current.[65,66] Further downstream, the Agulhas Return Current could link the proposed MPAs in ABNJs with large MPAs found in national waters of France and the United Kingdom in the Southern Ocean (Prince Edward Island, French Austral Land and Seas, McDonald Island).[65] In the northwest, the South Equatorial Current could connect MPAs in British Overseas Territories (Chagos, Amirante, Aldabra Atoll) with the proposed MPA over the Mascarene Plateau. The South Equatorial Current connects these biodiversity-rich areas to the coasts of Kenya and Somalia, improving food security.[40]

In the northern Indian Ocean, the mining-specific and shipping-specific plans could be complemented with OECMs to ensure better connectivity with the Red Sea and MPAs off the Omani coast, which may nonetheless be realized seasonally in all spatial plans, depending on monsoons.[67] Fishing-specific, shipping-specific, and cross-sectoral MPAs in the eastern Indian Ocean (e.g., over the northern part of Ninety East Ridge) could be connected to the Coral Triangle through the South Java Current and to Australian MPAs through the Leeuwin Current. The establishment of OECMs around Christmas and Cocos islands could provide further stepping stones for key life-cycle events in that region.[68]

Caveats

There are several caveats in our study that should be considered. First, to calculate the opportunity cost for the mining sector we used mean values for the crust thickness,[57] bulk density,[57] and mineral composition[37,69,70] in the area where minerals are found,[38] as more detailed spatial information was unavailable. Second, although we used metal prices predicted over the next decade,[71] uncertainty in future metal prices is high given their history of fluctuations in global markets.[72] Third, there are no publicly available estimates of the amount of mineable polymetallic sulfides in the Indian Ocean, which, unlike nodules or crusts, are found within vents and under the seafloor to unknown depths. Therefore, we removed areas where sulfide exploration contracts have already been issued but could not add the value of this resource to our cost layer. Yearly production data could be calculated after exploitation commences in the coming decade.[28] Fourth, while opportunity costs are not directly comparable across sectors in monetary terms, we used a relative opportunity cost, expressed as the percentage of the total possible opportunity cost for that sector, which enabled comparison across sectors. The opportunity cost for each sector was expressed in units most relevant for that sector, in line with available data.[28,38,73] Fifth, the spatial resolution of 1,000 km^2 yields over 33,000 planning units covering the planning region. While this is relatively coarse and might miss sub-grid-scale processes

Please cite this article in press as: Fourchault et al., Generating affordable protection of high seas biodiversity through cross-sectoral spatial planning, One Earth (2023), https://doi.org/10.1016/j.oneear.2023.12.006

that could be important for biodiversity,[12,20] a coarser spatial scale is often suitable in the open ocean.[13,21,74] Sixth, although shipping impacts could be minimal in ABNJs, there is evidence that ship strikes might be more important than previously thought.[14] Seventh, although we used 8-year-old ship traffic data,[38] the location of major shipping routes is unlikely to have substantially changed. More recent data on shipping traffic in the Indian Ocean were held by private companies. Eighth, we did not consider migratory connectivity[75] or larval circulation[21] in the reserve design, although both could benefit both biodiversity and food security.[40,65] Last, we manually adjusted the protection target for active hydrothermal vents to 68% rather than 70% (Figure S2). The initial target of 70% that was assigned to vents because of their high vulnerability[33] could not be met because numerous vents in the Indian Ocean overlap with sulfide exploration contracts.

Conclusions

This study develops a novel approach for systematic conservation planning in ABNJs. It integrates biodiversity features from the ocean surface to the seafloor, while considering the interests of three major maritime stakeholders: the fishing, shipping, and deep-sea mining sectors. We found that there were economic benefits and smaller areas protected in the cross-sectoral plan compared with sector-specific planning, and the fishing sector was the primary driver of the cross-sectoral plan.

As human activity expands into ABNJs, steps are being taken to better manage its impacts.[23,24,52] Marine conservation is gaining momentum globally with the 2021–2030 United Nations' Decade for Ocean Science and Sustainable Development, the expansion of area-based conservation targets under the Kunming-Montreal Global Biodiversity Framework, and the recently signed High Seas Treaty to protect biodiversity beyond national jurisdiction.[4,76] We hope that the methodology developed here can stimulate research into cross-sectoral MPAs that will better protect marine life.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Léa Fourchault (lea.fourchault@wanadoo.fr, lfourchault@naturalsciences.be).

Materials availability

All data reported in this paper will be shared by the lead contact upon request.

Data and code availability

All the code has been deposited at https://github.com/tropileaf/Indian-Ocean-SCP and will be made publicly available as of the date of publication.

Materials

Links to materials can be found in Table S2.

Methods

Software and packages

Spatial data were imported, rasterized, projected, cropped, overlaid with, and summed using the "raster," "terra," "sf," and "exactextractr" R packages (Tables S2 and S3). Spatial planning analyses were conducted using the "prioritizr" R package.[77]

Planning region

The planning region was the ABNJs of the Indian Ocean from 34°N to 45°S and from 018°E to 120°E to maximize the inclusion of ecological data of interest while excluding lower-quality fisheries cost data farther south (Figure 2A). The planning region was divided into 33,380 hexagonal planning units of 1,000 km^2 each using the Mollweide projection (ESRI:54009), with no depth limit.

Biodiversity data

We used the following biodiversity datasets to characterize key life-cycle areas and ecosystems across depth layers in the ABNJs of the Indian Ocean (Table S2 and Figures 2C–2H). Specifically, we used Important Bird Areas and Important Marine Mammal Areas as indicators of biodiverse and productive ecosystems, as these megafauna act as umbrella species for other species of concern[78] (Figures 2C and 2D). We also included some areas identified by the Ecologically and Biologically Significant Area process of the Convention on Biological Diversity, which highlight areas that meet specific ecological criteria (Decision IX/20, Annex I)[76,79] (Figure 2E and Table S2). In addition, we included geomorphic features, such as inactive and active hydrothermal vents[80] and seamounts and plateaus,[32] taken from the Blue Habitats database (Figures 2F–2H). These features support benthic and demersal communities by offering a range of substrates and concentrating plankton-rich currents.[81] Although systematic conservation planning exercises often incorporate species-level data, we were unable to access suitable species-level data for our study area. For example, global species' range maps, such as those from AquaMaps or the International Union for Conservation of Nature (IUCN), could bias our analysis because their source biological observations have relatively limited coverage of the Indian Ocean and undersample key habitats in our planning region, such as seamounts[32] and the deep ocean.[82,83]

Conservation features and targets

We used the biodiversity datasets to define the conservation features for the spatial prioritization analyses (summarized in Table S2). To ensure adequate coverage of each conservation feature, we set a minimum (target) threshold for each conservation feature.[8,84] Using a class-based version of inverse-weighted range-based targets,[13] we assigned conservation targets based on the spatial extent and vulnerability of each conservation feature (Table S2). In line with aims of the IUCN for marine conservation by 2030,[85] we assigned a 30% representative conservation target to conservation features with large spatial extents (>1,000 planning units, i.e., 1,000,000 km^2) or that represent a group of widespread features, such as seamounts. By contrast, we assigned a protective target of 70% to smaller or vulnerable features.

Special areas data

We characterized anthropogenic activity in the study area to ensure that our spatial prioritizations are feasible given existing management practices. We obtained data to characterize the spatial extent of areas leased for deep-sea mining activities from the ISA in 2022. Since legal obligations and economic interests would impede implementation of MPAs in reserved and exploration areas,[28] we identified planning units covered by such areas (Figure 2B). When contractors from high-income nations are granted rights to mineral exploration areas by the ISA, they contribute reserved areas to lower-income nations, following the principle that international seafloor resources are the common heritage of humankind (1994 Agreement, Annex, Section 2). Both reserved and exploration areas are subject to habitat degradation, such as sediment compaction in line with mineral extraction, and may thus cause lower biodiversity and abundance over multiple decades.[49]

Opportunity cost data

We characterized opportunity costs for implementing MPAs to fishing, shipping, and deep-sea mining sectors separately. Other activities—including hydrocarbon mining, telecommunication cabling, and bioprospecting activities—were not considered, although they could be in the future.[3] We expressed opportunity costs as monetary loss (USD) due to foregone extractive activities for the fishing and deep-sea mining industries and in terms of numbers of affected ships (i.e., rerouted or canceled trips) for the shipping sector (Figure 3). We calculated these costs using the procedures discussed in the following sections.

Fishing. To estimate the cost layer representing the fisheries value (USD) of each planning unit, we multiplied a global database of catch (kg) and price (USD kg^{-1}) for each species caught.[13] For catch data, we used fishing records for 1,242 species of fish and invertebrates at 0.5° resolution[86] interpolated to account for missing values and including an estimate of illegal, unreported, and unregulated fishing recorded as discards. For the price data, we used the mean price of each species (USD) from the Sea Around Us dataset. These

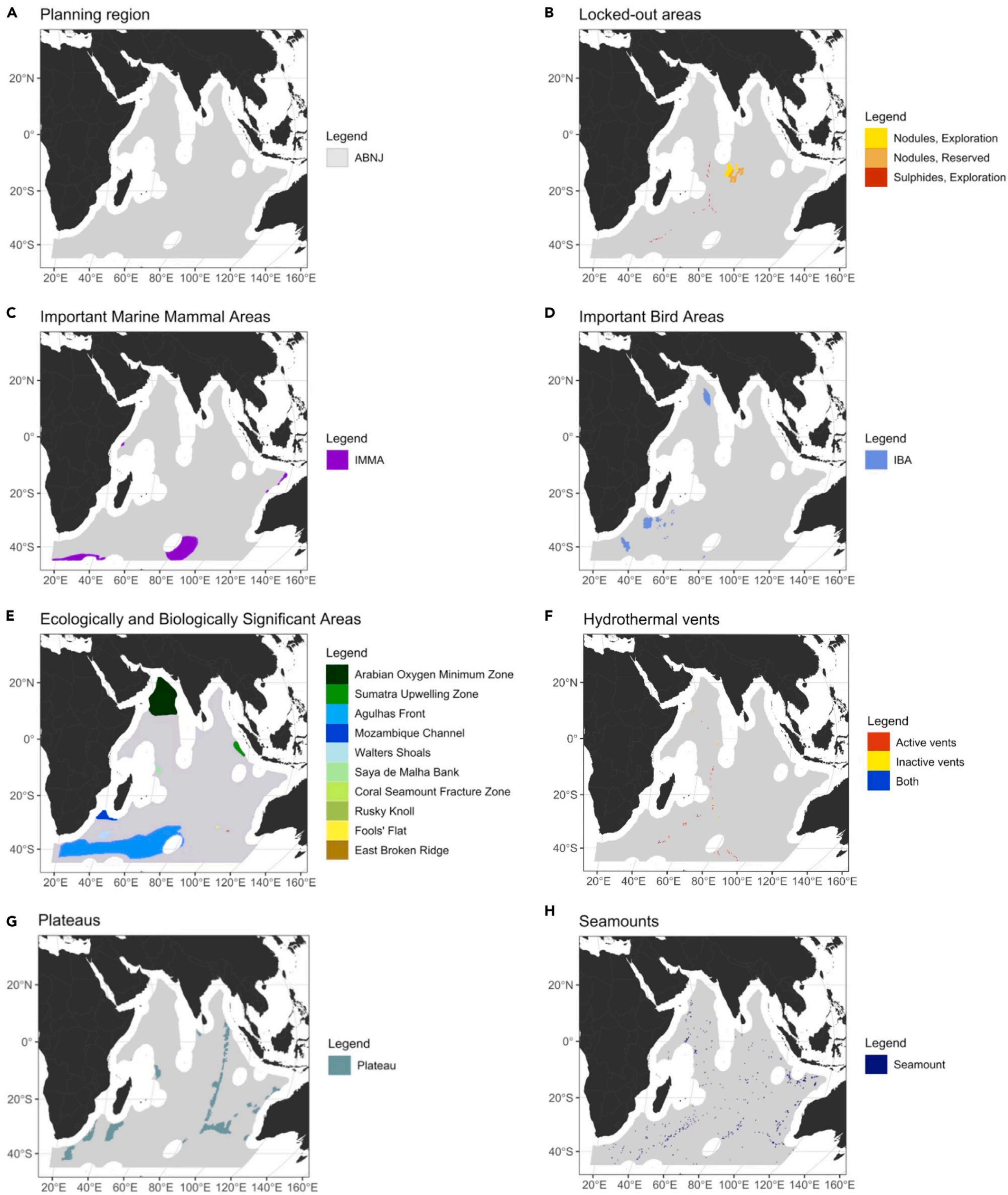


Figure 2. Input features

Maps show (A) planning region, (B) locked-out areas (related to mining), and (C–H) conservation features. In addition to various ecosystem types, conservation features include Ecologically and Biologically Significant Areas (EBSAs, features 1–10 described in Table S2), Important Marine Mammal Areas (IMMAs), and Important Bird Areas (IBAs). In the future, mining exploration areas and reserved areas are destined to define areas of commercial uses of deep-sea minerals (as per the International Seabed Authority's terminology).

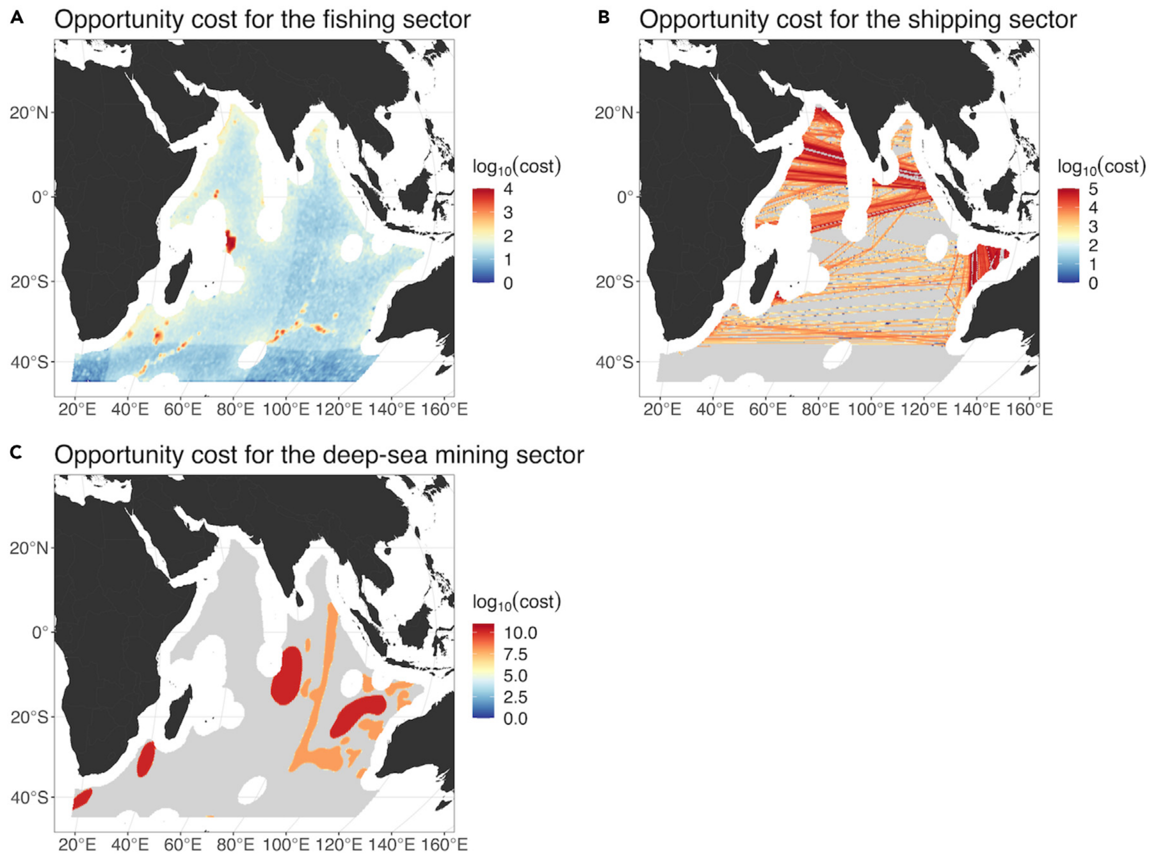


Figure 3. Opportunity cost layers

Maps showing the opportunity cost to (A) the fishing sector, (B) the shipping sector, and (C) the deep-sea mining sector. Details are described in Table S1.

estimates were summed within each planning unit and vary from USD 0.8 to 9,524 year^{-1}.

Shipping. To estimate shipping intensity, we obtained data from Halpern et al.[38] that delineated the spatial distribution of traffic density, expressed as the mean number of commercial vessels per year pixel (approximately 1 km^2 resolution). The opportunity cost was expressed as the number of ships affected (year^{-1}), i.e., trips that will be rerouted or canceled because of the proposed MPAs. These estimates for all planning units varied from 0 to 382,941 ships year^{-1}. In the future, the number of affected ships could be translated into monetary terms to facilitate comparison with other sectors: iterative stakeholder engagement could help estimate how MPAs might influence ship trajectories and extra costs of longer traverses.

Deep-sea mining. We created a cost dataset representing the future opportunity cost for the deep-sea mining sector based on two major deep-sea-mining resources: polymetallic nodules and cobalt-rich ferromanganese crusts (Figure 2).[69] Using spatial data from Petersen et al.[37] for mineral distribution, the total amount of resources within the planning region was calculated by multiplying surface area by deposit density (for polymetallic nodules) or crust thickness and bulk density (for cobalt-rich ferromanganese crusts).[69,70]

A monetary value was then assigned using predicted prices (USD) of copper, cobalt, and nickel multiplied by the average amount of metals (ppm) within each resource type.[28,69,71] Metal prices used in this analysis were based on those predicted over the coming decade (2020–2034[71]). Using the "raster" R package, a raster of the predicted value of polymetallic nodules and cobalt-rich crusts was applied to their distribution,[37] at a resolution matching that of the shipping and fishing rasters (1 km^2). The "exactextractr" R package was then used to obtain the value of each planning unit by summing the values of minerals contained within that planning unit (Table S3), with estimates varying from USD 0 to 14,307,812,352.

Data treatment

To ensure consistency in spatial data, vector data linked to the mining sector were rasterized at a resolution matching that of the raster layers for the shipping and fishing datasets (1 km^2; see Table S3). All spatial data were projected to an equal-area Mollweide projection. Temporal scales considered in this analysis partially overlap for the fishing and shipping dataset (2010s), with about a decade difference with the mining dataset (2020s/2030s). We used a relative opportunity cost expressed as a percentage of the total opportunity cost, so that if the total opportunity cost were to change in absolute terms (e.g., a rise in the number of vessels or the price of fish or a drop in metal prices after deep-sea mining commences on an industrial scale), the relative opportunity cost may still be representative of the impact of a no-take MPA on that sector.

Spatial prioritization

We created spatial plans using systematic conservation planning procedures.[6] Specifically, spatial plans were generated as prioritizations formulated using the minimum set objective.[13] This problem formulation aims to minimize a measure of cost while ensuring that conservation targets are met for all conservation features. Using this formulation, four prioritizations were generated. For the three sector-specific spatial plans, each planning unit had a value representing its importance for reaching conservation targets and a value representing its economic importance to the focal sector. The sector-specific spatial plans were generated by selecting areas that would result in the least cost to each sector, while still meeting the conservation targets.

The cross-sectoral spatial plan was generated to account for opportunity costs to the three sectors simultaneously. To achieve this, a multiobjective optimization technique was employed (based on the ε-constraint method). Briefly, instead of considering costs for each sector as part of the objective function for the optimization process, a set of linear constraints (one for each sector) was added to the problem formulation to ensure that the maximum cost associated with each sector would not exceed a particular threshold. An iterative procedure was then used to identify a suitable threshold for the threshold for each sector-specific constraint. The procedure started with setting the threshold values to be equal to the minimum opportunity costs identified in the sector-specific prioritizations (i.e., 19.5%, 0.6%, and 1.6% of the total possible opportunity cost for the fishing, shipping, and deep-sea-mining cost layers, respectively) (Table 1). Since attempting to solve this problem yielded infeasible solutions—because it was not possible to generate a prioritization that would satisfy all the targets for the conservation features and also satisfy all the sector constraints given these particular threshold values—each of the threshold values was incremented by 0.1% and then another prioritization was generated. This procedure was repeated until it yielded a feasible solution. Thus, the cross-sector prioritization satisfied the targets for all features for minimum cost across each of the three sectors, relative to the optimal cost that could be achieved when considering each sector separately.

All spatial plans were solved to optimality (gap = 0) using the Gurobi optimization solver.[87] Specifically, Gurobi uses exact algorithms, such as the branch and bound[88] and barrier algorithm,[89] with the additional functionality offered by presolve algorithms.[90]

Reserve characteristics

After generating the spatial plans, we performed several analyses to facilitate comparisons. First, each sector-specific spatial plan was analyzed using the replacement cost score (implemented in the “prioritizr” R package), a modified version of the economic exclusion cost.[91] This metric highlights areas of lower flexibility for planning unit selection. It corresponds to the additional cost incurred if a given planning unit cannot be acquired when implementing the solution and the next best planning unit needs to be selected instead. Second, we compared characteristics of all sector-specific and cross-sectoral spatial plans in terms of MPA size and relative opportunity cost. While the use of sector-specific units hinders a direct comparison among sectors, the comparison is made possible through the calculation of relative opportunity costs. The relative opportunity cost is the opportunity cost incurred for one sector, expressed as the percentage of the total possible opportunity cost for that sector. Last, we investigated whether the chosen conservation targets were met or exceeded. Targets can be exceeded when the cost of conserving a greater amount of the feature is null, i.e., when multiple features overlap or when a stakeholder has no economic interests in the area.

Sensitivity analysis

To evaluate the sensitivity of the sector-specific spatial plans to the chosen conservation features, we evaluated the change in reserve cost with and without each type of conservation feature (Table S1). We also evaluated the impact of the chosen targets on reserve size by increasing targets from 10% to 90% in 10% increments, where the fishing-specific MPA size increased linearly with increasing costs, while mining- and shipping-specific MPAs showed a lower increase, in line with larger initial reserves. To evaluate the sensitivity of the cross-sectoral spatial plan, we evaluated the reduction in size when simultaneously increasing sets of thresholds by 0.1% (i.e., maximal opportunity costs allowed for each sector).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.12.006.

ACKNOWLEDGMENTS

J.O.H. was supported by Environment and Climate Change Canada (ECCC) and Nature Conservancy of Canada (NCC). L.F., F.D.-G., S.C., and A.D. were supported by the Erasmus Mundus JMD in Tropical Biodiversity and Ecosystems (European Commission 2019-1451).

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, and project administration, A.J.R., D.C.D., J.D.E., L.F., K.K.A.S.Y., and F.D.-G.; software, J.O.H.; formal analysis and validation, L.F., J.O.H., K.C.V.B., S.N., J.D.E., and A.D.; data curation, J.D.E., L.F., and K.C.V.B.; visualization, L.F.; writing – original draft, L.F.; writing – review, all; supervision, A.J.R., D.C.D., J.D.E., K.K.A.S.Y., F.D.-G., and S.C.; funding acquisition, F.D.-G. and S.C.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: April 21, 2023
Revised: September 6, 2023
Accepted: December 7, 2023
Published: January 10, 2024

REFERENCES

1. Merrie, A., Dunn, D.C., Metian, M., Boustany, A.M., Takei, Y., Elferink, A.O., Ota, Y., Christensen, V., Halpin, P.N., and Österblom, H. (2014). An ocean of surprises – Trends in human use, unexpected dynamics and governance challenges in areas beyond national jurisdiction. Global Environ. Change *27*, 19–31.
2. Dunn, D.C., Jablonicky, C., Crespo, G.O., McCauley, D.J., Kroodsma, D.A., Boerder, K., Gjerde, K.M., and Halpin, P.N. (2018). Empowering high seas governance with satellite vessel tracking data. Fish Fish. *19*, 729–739.
3. Jouffray, J.B., Blasiak, R., Norström, A.V., Österblom, H., and Nyström, M. (2020). The Blue Acceleration: The Trajectory of Human Expansion into the Ocean. One Earth *2*, 43–54.
4. Gjerde, K.M., Harden-Davies, H., and Hassanali, K. (2022). High seas treaty within reach. Science *377*, 1241.
5. De Santo, E.M. (2018). Implementation challenges of area-based management tools (ABMTs) for biodiversity beyond national jurisdiction (BBNJ). Mar Policy *97*, 34–43.
6. Margules, C.R., and Pressey, R.L. (2000). Systematic conservation planning. Nature *405*, 243–253.
7. Ban, N.C., Bax, N.J., Gjerde, K.M., Devillers, R., Dunn, D.C., Dunstan, P.K., Hobday, A.J., Maxwell, S.M., Kaplan, D.M., Pressey, R.L., et al. (2014). Systematic Conservation Planning: A Better Recipe for Managing the High Seas for Biodiversity Conservation and Sustainable Use. Conserv Lett *7*, 41–54.
8. Holness, S.D., Harris, L.R., Chalmers, R., De Vos, D., Goodall, V., Truter, H., Oosthuizen, A., Bernard, A.T.F., Cowley, P.D., da Silva, C., et al. (2022). Using systematic conservation planning to align priority areas for biodiversity and nature-based activities in marine spatial planning: A real-world application in contested marine space. Biol. Conserv. *271*, 109574.
9. Chowdhury, S., Zalucki, M.P., Hanson, J.O., Tiatragul, S., Green, D., Watson, J.E.M., and Fuller, R.A. (2023). Three-quarters of insect species are insufficiently represented by protected areas. One Earth *6*, 139–146.
10. Millenium Ecosystem Assessment (2005). Ecosystem and Human Well-Being: Biodiversity Synthesis.
11. Clausen, R., and York, R. (2008). Global biodiversity decline of marine and freshwater fish: A cross-national analysis of economic, demographic, and ecological influences. Soc. Sci. Res. *37*, 1310–1320.
12. Arafeh-Dalmau, N., Brito-Morales, I., Schoeman, D.S., Possingham, H.P., Klein, C.J., and Richardson, A.J. (2021). Incorporating climate velocity into the design of climate-smart networks of marine protected areas. Methods Ecol. Evol. *12*, 1969–1983.
13. Brito-Morales, I., Schoeman, D.S., Everett, J.D., Klein, C.J., Dunn, D.C., García Molinos, J., Burrows, M.T., Buenafe, K.C.V., Dominguez, R.M., Possingham, H.P., et al. (2022). Towards climate-smart, three-dimensional protected areas for biodiversity conservation in the high seas. Nat. Clim. Change *12*, 402–407.
14. Womersley, F.C., Humphries, N.E., Queiroz, N., Vedor, M., da Costa, I., Furtado, M., Tyminski, J.P., Abrantes, K., Araujo, G., Bach, S.S., et al. (2022). Global collision-risk hotspots of marine traffic and the world's

largest fish, the whale shark. Proc. Natl. Acad. Sci. USA *119*. e2117440119.

15. Drazen, J.C., Smith, C.R., Gjerde, K.M., Haddock, S.H.D., Carter, G.S., Anela Choy, C., Clark, M.R., Dutrieux, P., Goetze, E., Hauton, C., et al. (2020). Midwater ecosystems must be considered when evaluating environmental risks of deep-sea mining. Proc. Natl. Acad. Sci. USA *117*, 17455–17460.
16. van der Grient, J.M.A., and Drazen, J.C. (2021). Potential spatial intersection between high-seas fisheries and deep-sea mining in international waters. Mar Policy *129*, 104564.
17. Claudet, J., Ban, N.C., Blythe, J., Briggs, J., Darling, E., Gurney, G.G., Palardy, J.E., Pike, E.P., Agostini, V.N., Ahmadia, G.N., et al. (2022). Avoiding the misuse of other effective area-based conservation measures in the wake of the blue economy. One Earth *5*, 969–974.
18. Schultz, M., Brun, V., Wingate, M., Cury, P., Gaill, F., Sicre, M.A., and Claudet, J. (2022). A framework to identify barriers and levers to increase the levels of protection of marine protected areas. One Earth *5*, 987–999.
19. Ban, N.C., and Klein, C.J. (2009). Spatial socioeconomic data as a cost in systematic marine conservation planning. Conserv Lett *2*, 206–215.
20. Almpanidou, V., Doxa, A., and Mazaris, A.D. (2021). Combining a cumulative risk index and species distribution data to identify priority areas for marine biodiversity conservation in the Black Sea. Ocean Coast Manag. *213*, 105877.
21. Combes, M., Vaz, S., Grehan, A., Morato, T., Arnaud-Haond, S., Dominguez-Carrió, C., Fox, A., González-Irusta, J.M., Johnson, D., Callery, O., et al. (2021). Systematic Conservation Planning at an Ocean Basin Scale: Identifying a Viable Network of Deep-Sea Protected Areas in the North Atlantic and the Mediterranean. Front. Mar. Sci. *8*, 800.
22. Ban, N.C., Maxwell, S.M., Dunn, D.C., Hobday, A.J., Bax, N.J., Ardron, J., Gjerde, K.M., Game, E.T., Devillers, R., Kaplan, D.M., et al. (2014). Better integration of sectoral planning and management approaches for the interlinked ecology of the open oceans. Mar Policy *49*, 127–136.
23. Davies, T.E., Carneiro, A.P.B., Campos, B., Hazin, C., Dunn, D.C., Gjerde, K.M., Johnson, D.E., and Dias, M.P. (2021). Tracking data and the conservation of the high seas: Opportunities and challenges. J. Appl. Ecol. *58*, 2703–2710.
24. Brooks, C.M., Bloom, E., Kavanagh, A., Nocito, E.S., Watters, G.M., and Weller, J. (2021). The Ross Sea, Antarctica: A highly protected MPA in international waters. Mar Policy *134*.
25. Rousseau, Y., Watson, R.A., Blanchard, J.L., and Fulton, E.A. (2019). Evolution of global marine fishing fleets and the response of fished resources. Proc. Natl. Acad. Sci. USA *116*, 12238–12243.
26. Techera, E.J. (2018). Supporting Blue Economy Agenda: Fisheries, Food Security and Climate Change in the Indian Ocean, pp. 7–27.
27. Farooq, M.S., Tongkai, Y., Jiangang, Z., and Feroze, N. (2019). Kenya and the 21st Century Maritime Silk Road: Implications for China-Africa Relations, pp. 401–418.
28. Sharma, R. (2022). Approach Towards Deep-Sea Mining: Current Status and Future Prospects. Perspectives on Deep-Sea Mining, 13–51.
29. Laran, S., Authier, M., Canneyt, O.V., Dorémus, G., Watremez, P., and Ridoux, V. (2017). A comprehensive survey of pelagic megafauna: Their distribution, densities, and taxonomic richness in the tropical Southwest Indian Ocean. Front. Mar. Sci. *4*, 139.
30. Thomas, P.O., Reeves, R.R., and Brownell, R.L. (2016). Status of the world's baleen whales. Mar. Mamm. Sci. *32*, 682–734.
31. Clark, M.R. (2009). Deep-sea seamount fisheries: a review of global status and future prospects. Lat Am J Aquat Res *37*, 501–512.
32. Marsac, F., Galletti, F., Ternon, J.F., Romanov, E.V., Demarcq, H., Corbari, L., Bouchet, P., Roest, W.R., Jorry, S.J., Olu, K., et al. (2020). Seamounts, plateaus and governance issues in the southwestern Indian Ocean, with emphasis on fisheries management and marine conservation, using the Walters Shoal as a case study for implementing a protection framework. Deep Sea Res. Part II Top. Stud. Oceanogr. *176*, 104715.
33. Thomas, E.A., Molloy, A., Hanson, N.B., Böhm, M., Seddon, M., and Sigwart, J.D. (2021). A Global Red List for Hydrothermal Vent Molluscs. Front. Mar. Sci. *8*.
34. Wright, G., and Rochette, J. (2017). Regional Management of Areas beyond National Jurisdiction in the Western Indian Ocean: State of Play and Possible Ways Forward. Int. J. Mar. Coast. Law *32*, 765–796.
35. Cohen, J. (1968). Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit. Psychol. Bull. *70*, 213–220.
36. Froese, R., and Pauly, D. (2002). FishBase: A Global Information System on Fishes.
37. Petersen, S., Krätschell, A., Augustin, N., Jamieson, J., Hein, J.R., and Hannington, M.D. (2016). News from the seabed – Geological characteristics and resource potential of deep-sea mineral resources. Mar Policy *70*, 175–187.
38. Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, J.S., Rockwood, R.C., Selig, E.R., Selkoe, K.A., et al. (2015). Spatial and temporal changes in cumulative human impacts on the world's ocean. Nat. Commun. *6*, 1–7.
39. Obura, D., and Ardron, J. (2012). Saya de Malha Bank. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=2ea49d95f5d99db215966bf81f85b9d137204448.
40. Popova, E., Vousden, D., Sauer, W.H.H., Mohammed, E.Y., Allain, V., Downey-Breedt, N., Fletcher, R., Gjerde, K.M., Halpin, P.N., Kelly, S., et al. (2019). Ecological connectivity between the areas beyond national jurisdiction and coastal waters: Safeguarding interests of coastal communities in developing countries. Mar Policy *104*, 90–102.
41. Ragionieri, L., Fratini, S., and Cannicci, S. (2015). Temporal patterns of megalopal settlement in different areas of an East African mangrove forest (Gazi Bay, Kenya). Hydrobiologia *749*, 183–195.
42. Schiller, L., Bailey, M., Jacquet, J., and Sala, E. (2018). High seas fisheries play a negligible role in addressing global food security. Sci. Adv. *4*, 8351–8359.
43. McCauley, D.J., Jablonicky, C., Allison, E.H., Golden, C.D., Joyce, F.H., Mayorga, J., and Kroodsma, D. (2018). Wealthy countries dominate industrial fishing. Sci. Adv. *4*.
44. Sala, E., Mayorga, J., Costello, C., Kroodsma, D., Palomares, M.L.D., Pauly, D., Rashid Sumaila, U., and Zeller, D. (2018). The economics of fishing the high seas. Sci. Adv. *4*.
45. Le Corre, M., Jaeger, A., Pinet, P., Kappes, M.A., Weimerskirch, H., Catry, T., Ramos, J.A., Russell, J.C., Shah, N., and Jaquemet, S. (2012). Tracking seabirds to identify potential Marine Protected Areas in the tropical western Indian Ocean. Biol. Conserv. *156*, 83–93.
46. Gopikrishnan, G.S., and Kuttippurath, J. (2021). A decade of satellite observations reveal significant increase in atmospheric formaldehyde from shipping in Indian Ocean. Atmos. Environ. *246*, 118095.
47. Chen, J., Bian, W., Wan, Z., Yang, Z., Zheng, H., and Wang, P. (2019). Identifying factors influencing total-loss marine accidents in the world: Analysis and evaluation based on ship types and sea regions. Ocean Engineering *191*, 106495.
48. O'Leary, B.C., and Roberts, C.M. (2018). Ecological connectivity across ocean depths: Implications for protected area design. Glob Ecol Conserv *15*, e00431.
49. Jamieson, A.J., Bond, T., and Vescovo, V. (2022). No recovery of a large-scale anthropogenic sediment disturbance on the Pacific seafloor after 77 years at 6460 m depth. Mar. Pollut. Bull. *175*, 113374.
50. Muñoz-Royo, C. (2018). Deep-sea Mining: Dewatering Plumes, Vortex-Induced Vibrations and Economic Modelling ([Doctoral dissertation] Massachusetts Institute of Technology).
51. Hilborn, R., and Kaiser, M.J. (2022). A path forward for analysing the impacts of marine protected areas. Nature *607*, 7917. E1–E2.
52. Smith, D., and Jabour, J. (2018). MPAs in ABNJ: lessons from two high seas regimes. ICES (Int. Counc. Explor. Sea) J. Mar. Sci. *75*, 417–425.

53. O'Leary, B.C., and Roberts, C.M. (2017). The structuring role of marine life in open ocean habitat: Importance to international policy. Front. Mar. Sci. *4*, 268.

54. Voyer, M., Moyle, C., Kuster, C., Lewis, A., Lal, K.K., and Quirk, G. (2021). Achieving comprehensive integrated ocean management requires normative, applied, and empirical integration. One Earth *4*, 1016–1025.

55. Maxwell, S.M., Hazen, E.L., Lewison, R.L., Dunn, D.C., Bailey, H., Bograd, S.J., Briscoe, D.K., Fossette, S., Hobday, A.J., Bennett, M., et al. (2015). Dynamic ocean management: Defining and conceptualizing real-time management of the ocean. Mar Policy *58*, 42–50.

56. Dunn, D.C., Maxwell, S.M., Boustany, A.M., and Halpin, P.N. (2016). Dynamic ocean management increases the efficiency and efficacy of fisheries management. Proc. Natl. Acad. Sci. USA *113*, 668–673.

57. Gelcich, S., Martínez-Harms, M.J., Tapia-Lewin, S., Vasquez-Lavin, F., and Ruano-Chamorro, C. (2019). Comanagement of small-scale fisheries and ecosystem services. Conserv Lett *12*.

58. Gurney, G.G., Darling, E.S., Ahmadia, G.N., Agostini, V.N., Ban, N.C., Blythe, J., Claudet, J., Epstein, G., Estradivari, Himes-Cornell, A., et al. (2021). Biodiversity needs every tool in the box: use OECMs. Nature *595*, 646–649.

59. Little, A.G., Loughland, I., and Seebacher, F. (2020). What do warming waters mean for fish physiology and fisheries? J. Fish. Biol. *97*, 328–340.

60. Cheung, W.W.L., Watson, R., and Pauly, D. (2013). Signature of ocean warming in global fisheries catch. Nature *497*, 365–368.

61. Robinson, R., Crick, H., Learmonth, J., Maclean, I., Thomas, C., Bairlein, F., Forchhammer, M., Francis, C., Gill, J., Godley, B., et al. (2009). Travelling through a warming world: climate change and migratory species. Endanger. Species Res. *7*, 87–99.

62. Anderson, J.J., Gurarie, E., Bracis, C., Burke, B.J., and Laidre, K.L. (2013). Modeling climate change impacts on phenology and population dynamics of migratory marine species. Ecol. Model. *264*, 83–97.

63. Crozier, L.G., Burke, B.J., Chasco, B.E., Widener, D.L., and Zabel, R.W. (2021). Climate change threatens Chinook salmon throughout their life cycle. Commun. Biol. *4*, 222.

64. Mendenhall, E., Hendrix, C., Nyman, E., Roberts, P.M., Hoopes, J.R., Watson, J.R., Lam, V.W.Y., and Sumaila, U.R. (2020). Climate change increases the risk of fisheries conflict. Mar Policy *117*, 103954.

65. Maina, J.M., Gamoyo, M., Adams, V.M., D'agata, S., Bosire, J., Francis, J., and Waruinge, D. (2020). Aligning marine spatial conservation priorities with functional connectivity across maritime jurisdictions. Conserv Sci Pract *2*.

66. Crochelet, E., Barrier, N., Andrello, M., Marsac, F., Spadone, A., and Lett, C. (2020). Connectivity between seamounts and coastal ecosystems in the Southwestern Indian Ocean. Deep Sea Res. Part II Top. Stud. Oceanogr. *176*, 104774.

67. Wang, Y., Raitsos, D.E., Krokos, G., Gittings, J.A., Zhan, P., and Hoteit, I. (2019). Physical connectivity simulations reveal dynamic linkages between coral reefs in the southern Red Sea and the Indian Ocean. Sci. Rep. *9*, 16598.

68. Przeslawski, R. (2021). AMSA Submission on the Proposal for the Establishment of Marine Parks in Australia's Indian Ocean Territories. https://www.amsa.asn.au/sites/default/files/AMSA%20Submission%202021_08_10%20Indian%20Ocean%20Territories%20Marine%20Parks%20Proposal.pdf.

69. Mizell, K., Hein, J.R., Au, M., and Gartman, A. (2022). Estimates of Metals Contained in Abyssal Manganese Nodules and Ferromanganese Crusts in the Global Ocean Based on Regional Variations and Genetic Types of Nodules. Perspectives on Deep-Sea Mining, 53–80.

70. Hein, J.R., and Koschinsky, A. (2014). Deep-ocean ferromanganese crusts and nodules. Treatise on Geochemistry, Second Edition 13, pp. 273–291.

71. Li, Y., Liu, C., Su, S., Li, M., and Liu, S. (2021). Analysis of the Effect of Payment Mechanism on Exploitation of Polymetallic Nodules in the Area. Minerals *11*, 221.

72. Rubaszek, M., Karolak, Z., and Kwas, M. (2020). Mean-reversion, non-linearities and the dynamics of industrial metal prices. A forecasting perspective. Resour. Pol. *65*, 101538.

73. Tai, T.C., Cashion, T., Lam, V.W.Y., Swartz, W., and Sumaila, U.R. (2017). Ex-vessel fish price database: Disaggregating prices for low-priced species from reduction fisheries. Front. Mar. Sci. *4*, 363.

74. Buenafe, K.C.V., Dunn, D.C., Everett, J.D., Brito-Morales, I., Schoeman, D.S., Hanson, J.O., Dabalà, A., Neubert, S., Cannicci, S., Kaschner, K., et al. (2023). A metric-based framework for climate-smart conservation planning. Ecol. Appl. *33*.

75. Dunn, D.C., Harrison, A.-L., Curtice, C., DeLand, S., Donnelly, B., Fujioka, E., Heywood, E., Kot, C.Y., Poulin, S., Whitten, M., et al. (2019). The importance of migratory connectivity for global ocean policy. Proc. Biol. Sci. *286*, 20191472.

76. Johnson, D., Barrio Froján, C., Bax, N., Dunstan, P., Woolley, S., Halpin, P., Dunn, D., Hazin, C., Dias, M., Davies, T., et al. (2019). The Global Ocean Biodiversity Initiative: Promoting scientific support for global ocean governance. Aquat. Conserv. *29*, 162–169.

77. Hanson, J.O., Schuster, R., Morrell, N., Strimas-Mackey, M., Edwards, B.P.M., Watts, M.E., Arcese, P., Bennett, J., and Possingham, H.P. (2023). Prioritizr: Systematic Conservation Prioritization in R. Preprint.

78. Dias, M.P., Oppel, S., Bond, A.L., Carneiro, A.P.B., Cuthbert, R.J., González-Solís, J., Wanless, R.M., Glass, T., Lascelles, B., Small, C., et al. (2017). Using globally threatened pelagic birds to identify priority sites for marine conservation in the South Atlantic Ocean. Biol. Conserv. *211*, 76–84.

79. Dunstan, P.K., Bax, N.J., Dambacher, J.M., Hayes, K.R., Hedge, P.T., Smith, D.C., and Smith, A.D.M. (2016). Using ecologically or biologically significant marine areas (EBSAs) to implement marine spatial planning. Ocean Coast Manag. *121*, 116–127.

80. Beaulieu, S.E., Baker, E.T., German, C.R., and Maffei, A. (2013). An authoritative global database for active submarine hydrothermal vent fields. G-cubed *14*, 4892–4905.

81. Genin, A. (2004). Bio-physical coupling in the formation of zooplankton and fish aggregations over abrupt topographies. J. Mar. Syst. *50*, 3–20.

82. Pavithran, S., Ingole, B., Nanajkar, M., and Nath, N.N. (2011). Macrofaunal Diversity in the Central Indian Ocean Basin, pp. 11–16.

83. Moudrý, V., and Devillers, R. (2020). Quality and usability challenges of global marine biodiversity databases: An example for marine mammal data. Ecol. Inf. *56*, 101051.

84. Carwardine, J., Klein, C.J., Wilson, K.A., Pressey, R.L., and Possingham, H.P. (2009). Hitting the target and missing the point: target-based conservation planning in context. Conserv Lett *2*, 4–11.

85. Dinerstein, E., Vynne, C., Sala, E., Joshi, A.R., Fernando, S., Lovejoy, T.E., Mayorga, J., Olson, D., Asner, G.P., Baillie, J.E.M., et al. (2019). A Global Deal for Nature: Guiding principles, milestones, and targets. Sci. Adv. *5*.

86. Watson, R.A. (2017). A database of global marine commercial, small-scale, illegal and unreported fisheries catch 1950–2014. Sci. Data *4*, 1–9.

87. Gurobi Optimization, L.L.C. (2023). Gurobi Optimizer Reference Manual (Preprint).

88. Land, A.H., and Doig, A.G. (2010). An Automatic Method for Solving Discrete Programming Problems. In 50 Years of Integer Programming 1958-2008 (Springer Berlin Heidelberg)), pp. 105–132.

89. Karmarkar, N. (1984). A new polynomial-time algorithm for linear programming. In Proceedings of the sixteenth annual ACM symposium on Theory of computing - STOC '84 (ACM Press), pp. 302–311.

90. Achterberg, T., Bixby, R.E., Gu, Z., Rothberg, E., and Weninger, D. (2020). Presolve Reductions in Mixed Integer Programming. Inf. J. Comput. *32*, 473–506.

91. Cabeza, M., and Moilanen, A. (2006). Replacement cost: A practical measure of site value for cost-effective reserve planning. Biol. Conserv. *132*, 336–342.